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Dynamic Fracture Toughness Testing

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An optical technique for measuring the crack-tip opening displacement of pre-cracked three-point-bend specimens subjected to impact loading was developed. Procedures for computing a dynamic Load-CTOD plot were also developed; this enables one to determine the dynamic fracture toughness. Finite element analyses were used to verify and extend the procedures. Keywords:

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1 Statement of Problem

The problem is to develop an effective, and yet easy-to-use, experimental technique and procedure for determining the dynamic fracture toughness of materials. It is well-known that most metals become more brittle at lower temperatures, and it is suspected that many of them become less tough at higher loading rates such as might be achieved by explosion or impact. A valid means of measuring the dynamic fracture toughness as a material property would be of tremendous benefit in understanding the basic mechanics and microstructural response of armor and structures. Further, it would serve an important role in quality control of material.

Routine fracture toughness testing at slower rates uses precracked specimens whose response has been calculated so that the material property K_c or J_c can be determined from remote measurements of the load and crack mouth opening displacement. In other words, one works from a plot of load versus displacement. This approach is not satisfactory for high-rate loading because the wave propagation effects mean that the local response at the crack tip can no longer be inferred from remote measurements. The time scale of interest here is on the order of tens of microseconds, and this is what makes the measurement difficult.

The central experimental technique of this research is the laser-based Interferometric Strain/ Displacement Gage, ISDG, which measures the in-plane relative displacement between two tiny indentations placed across the pre-crack near its tip. The indentations are nominally 100 micrometers apart and 100 micrometers behind the crack tip which reduces the problem of wave propagation effects. The motion of the indents characterizes the state of deformation local to the crack tip.

Small (55 millimeter long) three-point-bend specimens are precracked in fatigue to half their width and centrally loaded by impact from a gas gun. The indentations are illuminated with a 15 mW He-Ne laser, and the resulting fringe patterns are monitored with high-speed photomultiplier tubes and a digital oscilloscope. Needless to say, the major effort of this program went into developing these measurement techniques.

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Tests at three rates were run on steels and tungsten:

1. Quasistatic tests in an electrohydraulic test machine with test times on the order of minutes. CTOD was measured with photosensitive resistors, and the load and crack mouth displacement were measured with a load cell and a clip gage. This is a standard ASTM type of test, and the CTOD was simply recorded for comparison with later tests.

2. Intermediate rate tests in the same electrohydraulic test machine running at its fastest rate with a test duration on the order of tens of milliseconds. CTOD was measured with inexpensive phototubes, load with the load cell and crack mouth displacement with a clip gage. Similar tests were run in a drop tower at approximately the same rate.

3. Impact tests with a test duration of tens of microseconds. Only the CTOD versus time could be directly recorded here. This was turned into a dynamic load-displacement plot by assuming a linear loading rate based on the initial linear CTOD-time response which corresponds to elastic behavior.

Finite element analyses were used to model both the quasistatic and impact fracture events. In both cases, the CTOD history was successfully simulated by computing the motion of the indents and comparing it with experiment. For the quasistatic test simulation, the load history was known and only the specimen needed to be modelled.

In the dynamic finite element analyses of impact fracture, the loading on the specimen is not known and thus the specimen, tup, and projectile must be modelled to capture all the complex stress-wave interactions. The initial conditions are the velocity of the projectile which is measured in each experiment. For such high loading rates, it was found that material rate sensitivity played a major role in the transfer of load from the impact point to the crack, significantly affecting the CTOD versus time response. The finite element analyses supported the assumption of a linear dynamic loading rate at the crack tip on the order of $5 \times 10^6 MPam^{1/2}$ per second.

Dynamic elastoplastic finite element analyses that modeled the geometry and material supported the assumption of linear dynamic loading. These analyses can incorporate material rate effects and provide an extra level of sophistication for this difficult experimental problem.

2 Significant Results

- Dynamic CTOD can be easily measured on small specimens to produce an accurate record of the response <u>at the crack tip</u>. This technique can be extended to other temperatures and environments (such as radioactive or high electromagnetic fields) and to other modern materials — ceramics and metal matrix composites for example.

- Interpretation of the dynamic results is highly dependent upon the initial linear region of response. However, the procedure yields dynamic K_c values that have an accuracy of $+10/-20\%$. This seems large, but quasistatic measurements often show variations of $\pm10\%$.

- 2-D dynamic finite element models predict the CTOD versus time response after the closure load is exceeded if material rate-sensitivity is taken into account.

- The dynamic finite element simulations can be used to determine the dynamic J-integral and other important field quantities, as well as to improve the quantification of dynamic fracture toughness. method of knowing whether or not to consider high-rate loading effects.

3 Publication List

- "Dynamic Measurement of CTOD", W. N. Sharpe, Jr., Z. Waclawiw, and A. S. Douglas, *Fracture Mechanics: Nineteenth Symposium*, American Society for Testing and Materials, pp. 466-481, (1988).

- "Fracture Initiation under Impact Loading", A. S. Douglas and W. N. Sharpe, Jr., presented at IMPACT '87, Bremen, FRG, May 1987, and published in *Impact Loading and Dynamic Behavior of Materials*, Informationsgesellschaft-Verlag, 153-159, 1988.

- "Dynamic Fracture Toughness Evaluation by Measurement of CTOD", W. N. Sharpe, Jr., A. S. Douglas, and J. M. Shapiro, 80 page interim technical report submitted to ARO, March 15, 1988.

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- "Impact Fracture of a High Strength Steel", A. S. Douglas and M. S. Suh, presented at the 21st Symposium on Fracture Mechanics, Annapolis, MD, June 28-30, 1988. To appear in an ASTM Special Technical Publication (edited by J. P. Gudas), American Society of Testing and Materials, 1989.

- "Dynamic K Measurements in Three-Point-Bend Specimens", W. N. Sharpe, Jr. and J. M. Shapiro, in press, The Journal of Testing and Evaluation.

The technical report of March 1988 contains details of the experimental measurements and the finite element analyses and presents the results. It is a comprehensive report on the entire research project. At least one more major publication is planned base on the Master's essay of a fellowship student who is finishing in May 1988.

4 Scientific Personnel

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Master's Candidates

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- R. Tregoning, M.S., May, 1989.

Postdoctoral Fellows

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- Dr. M. S. Suh, Academic Year 1987-88.

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